

The ground-based large-area wide-angle γ -ray and cosmic-ray experiment HiSCORE

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Abstract

The question of the origin of cosmic rays and other questions of astroparticle and particle physics can be addressed with indirect air-shower observations above 10 TeV primary energy. We propose to explore the cosmic ray and γ -ray sky (accelerator sky) in the energy range from 10 TeV to 1 EeV with the new ground-based large-area wide angle ($\Delta\Omega \sim 0.85$ sterad) air-shower detector HiSCORE (Hundred**i* Square-km Cosmic ORigin Explorer). The HiSCORE detector is based on non-imaging air-shower Cherenkov light-front sampling using an array of light-collecting stations. A full detector simulation and basic reconstruction algorithms have been used to assess the performance of HiSCORE. First prototype studies for different hardware components of the detector array have been carried out. The resulting sensitivity of HiSCORE to γ -rays will be comparable to CTA at 50 TeV and will extend the sensitive energy range for γ -rays up to the PeV regime. HiSCORE will also be sensitive to charged cosmic rays between 100 TeV and 1 EeV.

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1. Introduction

The fundamental question of the origin of charged cosmic rays at knee energies remains unsolved. Indirect air-shower observations of ultra-high energy γ -rays (UHE γ -rays, $E > 10$ TeV) and cosmic rays above 100 TeV are the key to the solution of this question. Additionally, fundamental questions of particle physics can be addressed with the same air-shower data and might partly have an influence on its interpretation. Among these particle-physics topics are the measurement of the proton-proton cross-section, search for quark-gluon plasma in air-showers, axion search in the Galactic magnetic field, search for Lorentz invariance violation and for heavy super-symmetric particles (wimpzillas).

Cosmic rays. HiSCORE will provide spectral and composition measurements of cosmic rays over four decades in energy, from 100 TeV to 1 EeV. In the past decades, many experiments have measured the energy spectrum and chemical composition of cosmic rays over a wide range in energy. Existing data suggests a Galactic origin of cosmic rays up to $\approx 10^{17}$ eV (e.g. [Hörandel, 2003](#); [Blümer, Engel, Hörandel, 2009](#), for reviews). The transition from a Galactic to an extragalactic origin of the observed cosmic rays is believed to occur in the energy range between 10^{15} eV to 10^{17} eV. Above 10^{17} eV, com-

position is very poorly understood and compositions ranging from proton to iron dominated primaries are reported ([Anchordoqui et al., 2004](#), and references). A cosmic ray anisotropy on a large scale was observed in the northern hemisphere at TeV energies by the Tibet air-shower array ([Amenomori et al., 2006](#)) and confirmed by the Super-Kamiokande-I detector ([Guillian et al., 2007](#)) and Milagro ([Abdo et al., 2009](#)). Observations with IceCube yield a consistent structure in the southern sky ([Abbasi et al., 2010](#)). The origin of this anisotropy remains uncertain.

Origin of Galactic cosmic rays. The presence of CR accelerators throughout our Galaxy was clearly demonstrated by observations of diffuse γ -ray emission along the Galactic plane by EGRET ([Hunter et al., 1997](#)) and by later detections of extended γ -ray emission at VHE ([Aharonian et al., 2006](#); [Abdo et al., 2007](#); [Aharonian et al., 2008](#)). These emissions are most likely produced in interactions of energetic CRs with diffuse gas. Such extended molecular gas cloud structures thus act as CR tracers (see also [Gabici & Aharonian, 2007](#)). The observation of UHE γ -ray emission from extended gas clouds “illuminated” by nearby cosmic ray sources might open up a possibility to map the Galactic cosmic ray energy density. Assuming that the origin of cosmic rays is Galactic up to 10^{17} eV, there must be objects within our Galaxy that accelerate cosmic rays up to PeV energies: the cosmic ray pevatrons. Due to the typical inelasticity of neutral pion production in proton–proton collisions, pevatrons are ex-

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pected to exhibit γ -ray spectra up to several 100 TeV. Shell-type supernova remnants (SNR) are believed to be the prime candidates for the acceleration of Galactic cosmic rays. However, in the TeV energy regime, the observed emission is ambiguous since it can also be explained in a leptonic (inverse Compton) radiation scenario (see [Morlino, Amato, & Blasi, 2009](#), for a review). Recent results on the shell-type SNR RX J1713-3946 from the Fermi satellite ([Abdo et al., 2011](#)) yield a hard spectrum in the GeV energy regime. While these observations support a leptonic emission mechanism, they might also be explained as hadronic emission from dense cloud clumps ([Zirakashvili & Aharonian, 2010](#)), or when taking into account cosmic ray diffusion into molecular clouds ([Gabici & Aharonian, 2007](#)). Also see ([Inoue, Yamazaki, Inutsuka, & Fukui, 2011](#)), for a discussion of thermal X-rays from RX J1713-3946. Furthermore, the γ -ray luminosities of the detected objects are lower than expected, and the observed spectra are soft or have cut-off energies in the TeV energy regime, i.e. these objects cannot currently be cosmic ray pevatrons. Finding the cosmic ray pevatrons requires a survey of a large part of the sky in the UHE γ -ray regime. Interestingly, the leptonic/hadronic ambiguity disappears in the UHE regime, where the inverse Compton scattering cross-section drops with increasing center of mass energy (Klein-Nishina regime). At 100 TeV, the inverse Compton effect takes place in the deep Klein-Nishina regime for electrons scattering off photons from the cosmic microwave background (CMB). This results in inevitably soft

γ -ray spectra from leptonic accelerators beyond 10 TeV. As opposed to that, a hard γ -ray spectrum continuing up to few hundred TeV would be a clear signature of hadronic acceleration.

Origin of extragalactic cosmic rays. Assuming the origin of cosmic rays beyond 10^{17} eV is extragalactic, an enhancement of cosmic rays beyond this energy from the direction of the local super-cluster can be expected ([Kneiske & Horns, 2010](#)). These cosmic rays can interact with the CMB, initiating intergalactic secondary cascades that could be observable in γ -rays. The emission is expected to match the structure of the local super-cluster and would be measurable as anisotropic emission in the total field of view of the experiment. Alternatively, the accelerators of extragalactic cosmic rays might exhibit point-like emission or halo-like structures resulting from the interactions of the accelerated particles with the surroundings of the source.

Gamma-ray propagation and the hidden sector. At such high energies as considered here, γ -rays are attenuated via e^+e^- -pair-production with the photons of low energy radiation fields, such as the cosmic microwave background (CMB), the extragalactic background light, the supergalactic radiation field or the Galactic interstellar radiation fields (IRF). Within our Galaxy, the dominant radiation fields are the IRF and the CMB. The attenuation reaches a maximum for Galactic objects around 100 TeV from the Galactic IRF and at 2 PeV from the CMB ([Moskalenko, Porter, & Strong, 2006](#)).

While the former depends on the Galactic longitude and local radiation fields, the latter is universal. If the distance of the observed γ -ray sources is known, the density of the IRF might be inferred from the strength of the absorption by pair production (or from spectral features). Inversely, Galactic absorption might also open up a new possibility to infer distances from the measurement of γ -ray spectra, if the IRF in the line of sight is known. Such a new method for distance estimation of Galactic objects might also be possible if the universal absorption by the CMB could be measured. The expected attenuation by pair production might be altered by photon/axion conversion (e.g. [Stefen, 2009](#)). Photons produced at the source travelling through the Galactic magnetic field might convert into axions propagating without absorption. If a reconversion of these axions back into photons happens before arriving at Earth, the photon signal would appear to be stronger than expected. The same effect could arise if photon/hidden-photon oscillations ([Zechlin, Horns, & Redondo, 2008](#)) would occur. Another effect that might alter the expected absorption by pair production is the modification of the e^+e^- pair production threshold in case of Lorentz invariance violation.

1.1. A new non-imaging UHE detector: HiSCORE

The sensitivity level of existing and currently planned γ -ray detectors is optimized to the very high-energy regime (VHE, $100 \text{ GeV} < E < 10 \text{ TeV}$). The sensitivity to the UHE γ -ray regime (UHE γ -rays, $E > 10 \text{ TeV}$)

is limited because previously, the trend in development of detectors for γ -ray astronomy was dominated by the focus on low energy thresholds. Future and planned experiments such as CTA ([CTA Consortium, 2010](#)), HAWC ([Sinnis, 2005](#)), TenTen ([Rowell et al., 2008](#)), or LHAASO ([Cao, for the ARGO-YBJ Collaboration, & the LHAASO Collaboration, 2010](#)) will improve the situation in the UHE γ -ray regime. However, due to dropping event statistics with rising energy, the key to UHE γ -ray astronomy is a very large instrumented area of the order of 10 to 100 km². While such large instrumented areas seem impracticable using the well-established imaging air Cherenkov technique (order of 10 000 channels/km²), the non-imaging air Cherenkov technique provides a complementary possibility that comes along with some advantages, such as a small number of channels per km² (less than 100 per km²) and a wide field of view (order of sr). We have started the development of HiSCORE (Hundred Square-km Cosmic ORigin Explorer), a ground-based wide-angle large-area air-shower detector for non-imaging γ -ray astronomy and cosmic ray physics from 10 TeV to 1 EeV. With its wide field of view (continuously monitoring a large part of the sky) and a focus on the highest energies, this project is complementary to (yet independent of) existing and planned experiments.

Optimized for the UHE γ -ray regime and for cosmic ray energies from 100 TeV to 1 EeV, HiSCORE will allow to address the γ -ray and cosmic ray physics topics introduced in the previous section.

2. HiSCORE detector design

The HiSCORE detector principle is based on the shower front sampling technique using Cherenkov light. The detector consists of a large array of wide-angle light-sensitive detector stations, that measure the light amplitude and the entire longitudinal development using the shower-front arrival-time distribution (at distances from the shower core >100 m). These measurements allow detailed spectral and composition measurements, and γ -hadron separation via reconstruction of the shower-depth. The concept of the detector modules used as working assumption for the HiSCORE detector was adapted from previous γ -ray experiments, such as THEMISTOCLE (Fontaine et al., 1990; Behr et al., 1991), HEGRA AIROBICC (Karle et al., 1995), or BLANCA (Cassidy et al., 1997). Similar detector modules are also used in the TUNKA array for cosmic-ray physics (Budnev et al., 2005). As compared to TUNKA, three aspects of HiSCORE will be different: an instrumented area larger by more than an order of magnitude, larger detector station areas (factor 16) and larger inter-station spacing. Advances made in technology allow improvements to the original detector components such as improved photo-sensitive detectors, and fast trigger and readout electronics, therewith allowing a measurement of the Cherenkov photon arrival time distribution.

A very large instrumented area is required to reach sufficiently large event statistics in the UHE regime, and is achieved with a low array density, i.e. large inter-station spacings. A reasonable value for the detector sta-

tion spacing can be derived from the lateral photon density function (LDF) of Cherenkov light (300 nm to 600 nm) at observation level, shown in Figure 1. Within a radius of 120 m around the shower core position the LDF is roughly constant, but shows a large spread from shower to shower. Fluctuations are much lower beyond 120 m. With the envisaged station spacing of 100–200 m, only few stations are within the inner 120 m of the LDF, shown in Figure 1. Thus, HiSCORE will primarily sample the outer part of the LDF. The low photon density far away from the shower core justifies the chosen large individual detector station areas. For comparison, the corresponding sensitive range of the AIROBICC experiment is also shown (grey dashed line). This figure demonstrates the basic difference in scale: The inter-station spacing of the HiSCORE array is of the same order of magnitude as the total side-length of AIROBICC. Measurements of the LDF far away from the shower core provide a large lever-arm and thus good reconstruction quality. Another important aspect for the reconstruction with the HiSCORE detector is the usage of the full timing information from the arrival time distribution of the Cherenkov photons at each detector station. The event reconstruction of HiSCORE is based on the combination of information from the lateral photon density distribution and the arrival time distribution of Cherenkov photons (Hampf, Thuczykont, & Horns, 2009).

Each detector station consists of four photomultiplier tubes (PMTs) equipped with four light-collecting Winston cones of 30° half-opening angle pointing to the zenith. A

5 TeV (see discussion of hadron trigger rate below). The IACT option was used, storing Cherenkov photons in spheres of 1 m radius at sea-level, each sphere representing one detector. The array layout was simulated as a simple grid of 22×22 stations with an inter-station spacing of 150 m, covering a total instrumented area of $\approx 10 \text{ km}^2$ (3.15 km side-length). Air-showers were simulated over a larger area, with random impact position in a square with side-length 3.75 km. A full detector simulation (*sim_score*) was implemented on the basis of the *iact* package provided by [Bernlöhr \(2008\)](#). At the position of each CORSIKA sphere, a detector station with 4 PMT-channels is simulated in *sim_score*. The detector station simulation includes atmospheric absorption (MODTRAN [Kneizys et al., 1996](#)), ray-tracing tables for Winston cone acceptance, and PMT response (including afterpulses). The simulation of the station trigger (as illustrated in Figure 2) includes clipping of each individual PMT signals (to suppress the effect of afterpulses), analog summing of all four channels, and a discriminator. A local station trigger is issued when the sum of all four PMT signals passes a given threshold (few σ above NSB level). The resulting simulated digitized signals are stored and a bin-by-bin noise pedestal from a simulation of the expected NSB is added.

3.2. Cosmic ray trigger rates

The effective area at trigger level is given as the ratio of triggered to simulated events divided by the simulated area. Figure 3 shows the effective trigger areas (for γ s, H,

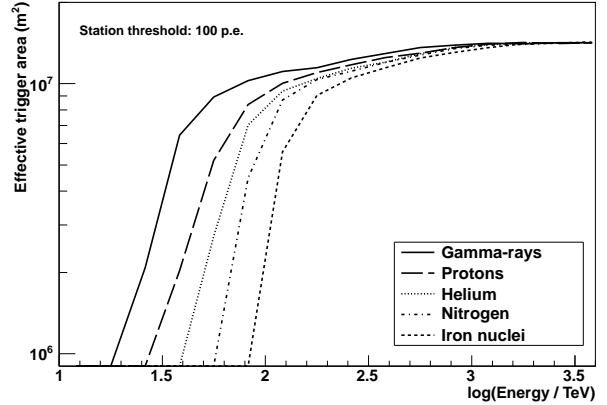


Figure 3: Effective areas A_{eff} of the HiSCORE detector at trigger level for different primary particle types. An array trigger is issued when one or more stations have a local trigger.

He, N, Fe) when using a station threshold of 100 photoelectrons (p.e.). As can be seen from the effective trigger areas, protons still trigger at low energies as opposed to heavier nuclei. This justifies the simulation of proton energies down to 5 TeV. Using these effective trigger areas and the *polygonato* parametrization for cosmic rays ([Hörandel, 2003](#)), a cosmic ray trigger rate of $\approx 1.8 \text{ kHz}$ was obtained for a 10 km^2 array. This corresponds to a local single-station cosmic ray trigger rate of $\approx 15 \text{ Hz}$. The data rate could be further reduced when using a two-fold next-neighbour station coincidence condition. Such a coincidence condition may be implemented at the software-level of the central data acquisition or using a hardware second-level trigger condition.

A simulation of the expected accidental local station trigger rate due to night-sky back-

ground (NSB) photons (PMT response including afterpulses) was implemented. Results from measurements of the NSB photon rate in Australia (Hampf et al., 2011) were used as input and a discriminator response gate with a width of 7 ns was assumed. At a discriminator threshold of 100 p.e., this simulation yielded an NSB trigger rate of the order of 100 Hz. This value clearly demonstrates that, at a station threshold of 100 p.e., the station trigger rate is dominated by NSB photons. First tests of the planned readout system yield a maximum data rate of the order of 100 Hz per station. Slightly increasing the station discriminator threshold to 105 p.e. results in an NSB trigger rate of 52 Hz without significantly affecting the sensitivity at reconstruction level (≥ 3 Stations and reconstruction cuts).

For the 10 km² stage of the array, the trigger rates ($E > 5$ TeV) of the different simulated cosmic ray particle-classes are 875 Hz ($Z=1$), 505 Hz ($Z=2-5$), 290 Hz ($Z=6-24$), and 103 Hz ($Z > 24$). In this detector stage, we expect of the order of 10^8 cosmic ray events per year above 100 TeV and still of the order of 5 events per year at 10^{18} eV. A γ -ness parameter² (Hampf, Tluczykont, & Horns, 2009) is used for γ -hadron separation and can also be used for a measurement of the chemical composition, ultimately providing an estimation of the mass-composition via the measurement of the shower depth. A similar approach is

used by the TUNKA detector (Budnev et al., 2005).

3.3. Gamma-ray sensitivity

The point-source survey sensitivity of HiSCORE to γ -rays was calculated using basic reconstruction algorithms introduced in Hampf, Tluczykont, & Horns (2009).

The performance of the reconstruction algorithms as applied to the Monte Carlo data set is summarized in Table 1. The fundamental differences between HiSCORE and an imaging air-shower array such as CTA are the much larger detector area of HiSCORE and the fact that HiSCORE, with its large field of view, will always simultaneously cover a large fraction of the sky. Therefore, HiSCORE always operates in *survey mode*, and any single source inside the large field of view will be visible over 200 h per year (calculated for a southern hemisphere site at a latitude of -35°), i.e. 1000 h after 5 years of survey operation. As opposed to that, IACTs operate in pointed mode and cannot allocate such long observation times to single sources. For example, in the H.E.S.S. survey (Aharonian et al., 2006) the time allocated to one pointing per year is typically of the order of 10 h, i.e. a factor of 20 lower than in the HiSCORE survey. At the same time, with a covered solid angle of π steradian for more than 200 h per year, HiSCORE covers a significantly larger fraction of the sky than the H.E.S.S. survey has covered.

To calculate the sensitivity to γ -rays, we required 5σ detection significance and a minimum of 50 γ -rays. The background was calculated on the basis of the simulated

²The γ -ness parameter is defined on the basis of the reconstructed shower depth and energy and the light concentration on the ground.

Table 1: Performance of the employed basic reconstruction algorithms for γ -ray analysis.

	50 TeV	100 TeV	>500 TeV
Angular resolution (68 %)	0.8°	0.3°	0.1°
Shower core position accuracy	40 m	20 m	8 m
Shower depth accuracy	150 g/cm ²	60 g/cm ²	20 g/cm ²
Energy resolution ($\Delta E/E$)	40 %	20 %	10 %

hadron effective areas after applying reconstruction cuts (at least 3 triggered stations, γ -ness > 6, contained events). The *polygono* parametrization (Hörandel, 2003) of the cosmic ray spectra for each nucleus-type was folded with the area corresponding to the closest nucleus out of the group of four simulated (proton, Helium, Nitrogen, Iron). The resulting point-source sensitivities for instrumented detector areas of 10 and 100 km² are shown in Figure 4 along with point-source sensitivities of other experiments (Bernlöhr, 2008; CTA Consortium, 2010; Amenomori et al., 2007; HAWC collaboration, 2011), and an upper limit by KASCADE (Antoni et al., 2004). HiSCORE will be complementary to other instruments in different ways. It will extend the energy range covered by CTA at a similar energy flux sensitivity level and cover a large fraction (π sr) of the southern sky. While the 10–100 km² stages of HiSCORE are planned for deployment in the southern hemisphere (best access to Galactic plane), the other survey instruments shown here (AS γ +MD and LHAASO) are northern hemisphere detectors, thus covering a different region of the sky.

At the energy threshold, the HiSCORE sensitivity is limited by the angular resolution and the γ -hadron separation. At the upper

energy end, the sensitivity is statistics limited and only depends on the total detector area and the exposure time (grey thin rising straight lines). Weak pevatrons (thin black line) that might be detectable below their cut-off energy regime by H.E.S.S. and Milagro will be well within reach of a 10 km² detector. The cut-off regime of such sources will be fully resolved with HiSCORE (100 km²).

4. Prototype development and engineering array

A prototype station is currently under development and hardware component tests are in progress. A test-bed for photomultiplier-tubes (PMTs) was developed. We are currently measuring signal shapes, gain values, and dynamic ranges. The dynamic range will be increased to the necessary factor of 10⁵ (10 TeV to 1 EeV) by reading out one or two dynodes in addition to the anode signal. A first prototype station with a single PMT-channel is currently under construction at the University of Hamburg. The aluminium housing is equipped with a sliding lid and also contains slow-control electronics, a high-voltage supply and distribution, and a read-out system. We plan the deployment of full (4-channel)

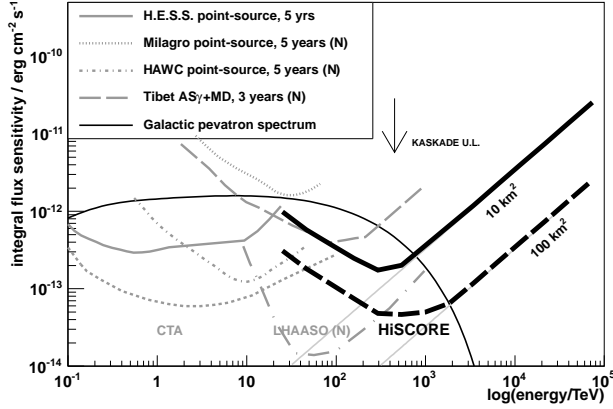


Figure 4: HiSCORE 5-year point-source survey sensitivity for 10 km² and 100 km² instrumented detector areas. For comparison, point-source sensitivities are given for the following experiments: H.E.S.S. (50 h), CTA (50 h), Milagro and HAWC (5-years), Tibet AS γ +MD (3 years), and LHAASO. In a survey-mode, the CTA and H.E.S.S. sensitivities will not reach the displayed level but will be significantly less powerful, because pointed instruments cannot cover as large a fraction of the sky as HiSCORE. Instruments located or planned to be located in the northern hemisphere are marked with (N).

prototype stations for field tests and cross-calibration on the Tunka-site in Russia. Observatory sites in the southern hemisphere, such as the AUGER site, are also considered for test deployments. Especially in view of the construction of a first stage of the HiSCORE array, a site in the southern hemisphere is interesting due to the better visibility of the Galactic plane. Relative timing accuracy can be a limiting factor for the quality of the reconstruction. We aim at a 1 ns relative time resolution. An already existing time-calibration will be available on the Tunka site, based on the usage of the carrier

frequency of optical fibers (also used for read-out). An improvement of the Tunka method to an accuracy of 1 ns is planned. Furthermore, an investigation of alternative time-calibration methods, such as radio-beacon usage, are planned (Schröder et al., 2010).

5. Summary and outlook

We propose to explore the accelerator sky with observations of cosmic rays (100 TeV to 1 EeV) and UHE γ -rays ($E > 10$ TeV) with the new wide-angle large-area air-shower detector HiSCORE. Fundamental questions of particle and astroparticle physics can be addressed with HiSCORE.

HiSCORE will open up the UHE γ -ray ($E > 10$ TeV) observation window. Around 50 TeV a sensitivity comparable to the currently planned CTA will be reached. HiSCORE will extend the sensitive energy range up to the PeV regime. Measurements of the cosmic ray spectrum and mass composition will be possible over 4 orders of magnitude, from 100 TeV to 1 EeV.

The final layout of the HiSCORE detector is under study. Varying detector station densities can be used to optimize the sensitivity over the whole energy range. This could be achieved using smaller cells with very small inter-station distances (order of 10 m) and a graded array structure, with increasing inter-station distances towards the array-edge. An enhancement of the duty-cycle (10 %, air-Cherenkov observations restricted to astronomical darkness) could be achieved by equipping the underside of the sliding station lids with scintillator material,

thus providing charged particle air-shower measurements during daytime. Furthermore, a possible combination of the HiSCORE station principle with imaging air Cherenkov telescopes is under study.

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